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Robert H. Daugherty

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Braking and Cornering Studies on an Air Cushion Landing System

Robert H. Daugherty
Langley Research Center
Hampton, Virginia

NASA
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and Space Administration

Scientific and Technical
Information Branch

SUMMARY

An experimental investigation was conducted to evaluate several concepts for braking and steering a vehicle equipped with an air cushion landing system (ACLS). The investigation made use of a modified airboat equipped with an ACLS. Braking concepts were characterized by the average deceleration of the vehicle. Reduced lobe flow and cavity venting braking concepts were evaluated in this program. The cavity venting braking concept demonstrated the best performance, producing decelerations on the test vehicle on the same order as moderate braking with conventional wheel brakes. Steering concepts were evaluated by recording the path taken while attempting to follow a prescribed maneuver. The steering concepts evaluated included using rudders only, using differential lobe flow, and using rudders combined with a lightly loaded, nonsteering center wheel. The latter concept proved to be the most accurate means of steering the vehicle on the ACLS, producing translational deviations two to three times higher than those from conventional nose-gear steering. However, this concept was still felt to provide reasonably precise steering control for the ACLS-equipped vehicle.

INTRODUCTION

As aircraft become larger and heavier, design of systems to support them during take-off and landing becomes more demanding. Today, some aircraft are restricted from operations on certain runways because of the possibility of damage to the runway surfaces. Providing adequate flotation for a heavy aircraft can incur large weight penalties. For example, the Lockheed-Georgia C-5 landing gear weighs about 52 000 lb (231 kN), approximately 7 percent of total gross weight, which includes the gear doors and their associated structure (ref. 1). Conventional landing gear requires an aircraft structure to withstand high localized loads. Also, this type of gear generally precludes operating on low-strength or unprepared surfaces.

An air cushion landing system (ACLS) offers a possible solution to these problems. An ACLS makes use of an inflatable air bag with peripheral jets at the ground tangent. High-volume, low-pressure air is introduced into the air bag and exhausts through the jets. Typically, an ACLS covers a large area, so only a very low ground bearing pressure is required to support a large aircraft. In general, low bearing pressure provides the capability to operate on a variety of surfaces, both prepared and unprepared, and may extend to amphibious operations.

At least two aircraft, the Lake LA-4 Amphibian and the De Havilland CC-115, have been fitted with an ACLS on an experimental basis. However, these aircraft were difficult to control and stop because they lacked conventional ground contact. These difficulties were especially pronounced at low speeds when aerodynamic control surfaces were ineffective (ref. 2). Small inflatable pillows, which were located between the air bag and the ground, were incorporated into both designs to provide brakes and differential braking for steering. However, this arrangement still did not eliminate the inherent sideslip and yaw of these two aircraft. Therefore, the tests on these aircraft emphasized the need for new control techniques.

The purpose of this paper is to present results of an experimental program conducted at NASA Langley Research Center in which several concepts for braking and steering a vehicle equipped with an ACLS were evaluated. In this investigation, candidate braking and steering systems were installed on a modified airboat fitted with an ACLS. Braking concepts were evaluated by measuring the distance required to stop from brake application speeds up to 45 ft/sec (14 m/sec) on concrete and grass surfaces. Steering tests were conducted at speeds up to 27 ft/sec (8 m/sec) while attempting to follow an S-shaped path painted on a runway and recording the ground track of the vehicle. Deviations from the test path were represented by maximum and average error terms.

APPARATUS

Airboat

The vehicle used in this investigation was a modified airboat shown in figure 1. The basic airboat was equipped with an aircraft engine, which supplied about 500 lb (2 kN) of thrust at full throttle. Engine thrust was used in conjunction with highly effective dual rudders to provide forward and turning motion for the vehicle. These large rudders were effective only when thrust was applied, since they were directly aft of the propeller. Retractable landing gear (one nose, two main) were added to the airboat and provided a means of obtaining baseline braking and steering data. An auxiliary power unit (APU) and a hub turbine fan were used to power the ACLS. The vehicle was approximately 22 ft (6.7 m) long, 12 ft (3.7 m) wide, and weighed approximately 5500 lb (24 kN) which included the operator and observer.

Air Cushion System

The air cushion system for the test vehicle consisted of the APU, hub turbine fan, plenum, and air bag. The hub turbine fan is shown in figure 2, and a photograph of the air bag is presented in figure 3. The APU is a gas turbine engine which provided bleed air to drive the hub turbine fan. High-temperature (400°F (204°C)), high-pressure (18 psig (124 kPa)) drive air from the APU caused the hub turbine to rotate and draw in ambient air through its tip fan. The combined flow rate of the hub turbine fan was approximately 120 ft^3/sec (3.4 m^3/sec) at full speed (about 20 000 rpm). This airflow was exhausted into the plenum, where air temperatures were stabilized and the flow was evenly distributed to the air-bag lobes. The air bag used on the vehicle consisted of four lobes rather than a single annulus commonly found on an ACLS. Each lobe was fabricated by "laying up" an open weave of Kevlar fabric (about 6 fiber bundles per inch) into a truncated circular shape and spraying it with polyurethane. The orifices in the bottom of each lobe were created by preventing the polyurethane from adhering to the fabric in those areas. The individual lobe design provided the capability of obtaining differential pressures between lobes of the air-bag system. The airflow through the orifices located at the ground tangent provided air lubrication for the system. The length and width of the air bag were 14.5 ft (4.4 m) and 8.5 ft (2.6 m), respectively, which provided an area in the center of the arrangement 9.5 ft by 3.5 ft (2.9 m by 1.1 m). This area is referred to as the cavity. Each lobe has a 1.25-ft (0.4-m) radius in cross section except for a flat cover. In normal operation, the covered cavity which was indirectly fed by the lobe orifices maintained a pressure of approximately 0.4 lb/in^2 (3.0 kPa). Each of the air-bag lobes maintained a pressure of about 0.8 lb/in^2 (5.5 kPa).

Test Area

For this investigation, the tests were conducted on an inactive concrete runway at Langley Air Force Base. The portion of the runway that was used measured 150 ft by 1400 ft (46 m by 427 m). The runway had a transverse slope of 1 percent. In addition, grass areas adjacent to the runway were used during some of the braking concept tests. Surface conditions for all tests were dry, and winds were negligible.

Instrumentation

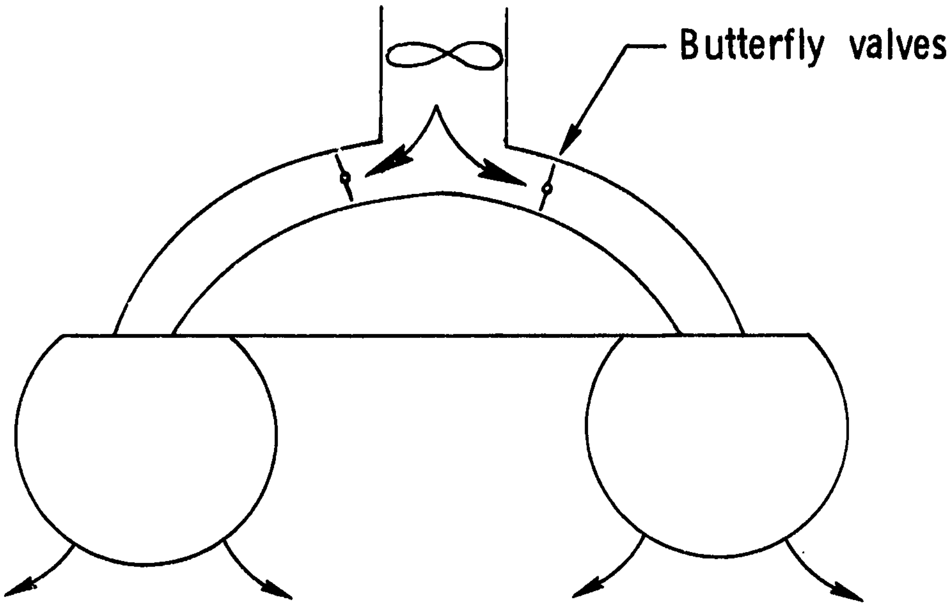
Parameters measured during each braking test were brake application speed and stopping distance. These measurements were obtained by using the trailing wheel shown in figure 4. This wheel produced a pulse count based on its rotation and gave a digital readout of speed and distance. Parameters measured during each steering test included vehicle velocity, heading angle, and yaw angle. Velocity measurements were recorded from a dc generator which was coupled to the trailing wheel. Heading measurements were recorded from a rate gyroscope which was coupled with an integrator. This device measured the angle between the longitudinal axis of the airboat and an inertial reference direction that was set before each test. The precession (Coriolis drift) rate of the gyroscope was small enough that during a typical test run the drift was on the order of 1° or less. This drift caused no significant errors in the data. Yaw angle measurements were recorded from a continuous-turn potentiometer mounted on the pivot of the trailing wheel. (See fig. 4.) The wheel assembly was free to pivot, so that any yaw angle the vehicle attained was measurable relative to the wheel which tracked in the direction of motion; however, small errors would occur if the vehicle moved slowly while the yaw changed rapidly.

BRAKING AND STEERING CONCEPTS

Braking

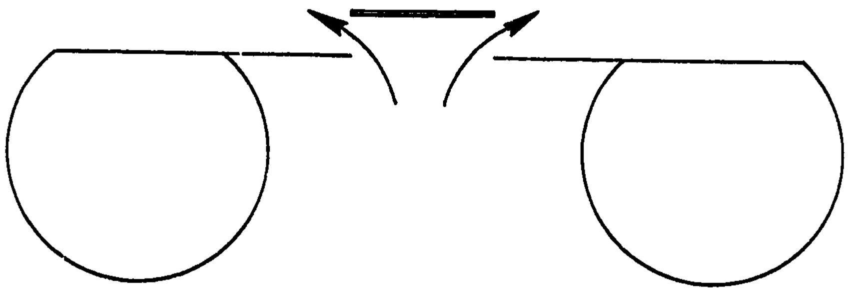
Several different concepts for stopping the vehicle were evaluated. Initially, however, two sets of tests were conducted to get baseline data. First, a set of tests were conducted with the conventional landing gear as installed on the vehicle and with the ACLS inoperative. The struts, wheels, tires, and brakes were from a light, twin-engine aircraft. A second set of tests were conducted using no braking. Instead, the vehicle was free to slide on the ACLS and relied only on air drag and friction between the air bag and the ground to bring it to a stop. This set of tests defined the lower boundary of the ACLS braking performance envelope.

The first ACLS braking concept was to use reduced airflow to three of the air-bag lobes. A schematic of this concept is shown in sketch A. Butterfly valves located in the feed hoses between the plenum and side and rear lobes could be adjusted from the cockpit to reduce the airflow into these lobes. This reduced lobe flow concept increased the friction between these air-bag lobes and the ground. Full pressure was maintained in the forward lobe to prevent the airboat from pitching nose down during the braking effort.



Sketch A

Shown in sketch B is the second ACLS braking concept, which involved venting the cavity. The cavity pressure provided approximately 40 percent of the total lift



Sketch B

force for the vehicle. Venting this pressure caused the vehicle weight to shift to the lobes which deflected, thereby increasing the friction between the air bag and the ground. To accomplish venting, a door in the top of the cavity was coupled to an electrically actuated air cylinder. This door is shown in figure 5. When activated, the cylinder retracts and the door opens approximately 3.5 in. (0.09 m). The dimensions of the door are 1.25 ft by 1.25 ft (0.38 m by 0.38 m). This area represents approximately 4 percent of the total cavity area.

Steering

Steering tests were conducted using four different concepts. The first series of tests used conventional nose-gear steering on the tricycle landing gear combined with rudders to define a baseline for comparison of steering while supported by the

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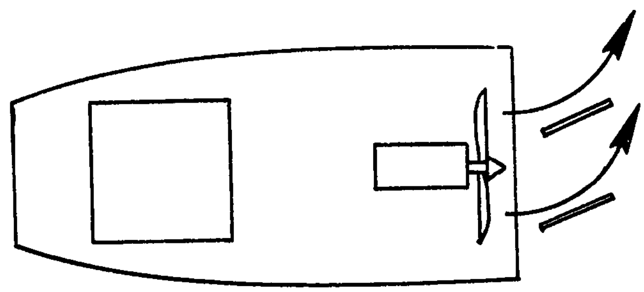
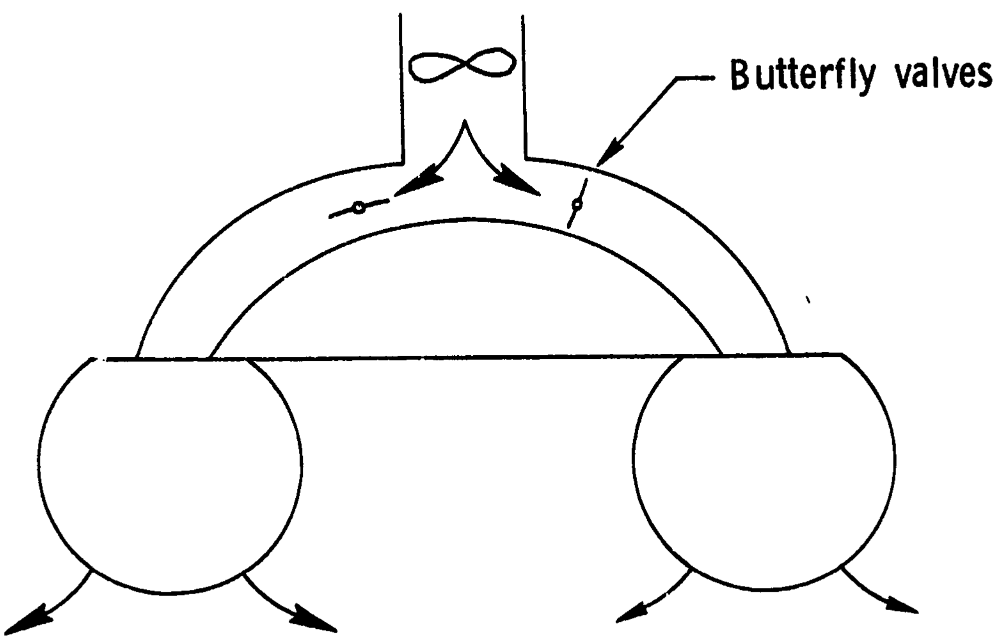
ACLS. A second series of tests were conducted on the air cushion using the rudders alone as the steering technique (rudders-only concept) and is shown schematically in sketch C. Since the rudders were effective only while thrust was maintained, the operator was instructed to apply thrust and yaw as necessary to accomplish the maneuver and to maintain speed. The third series of tests relied on differential lobe



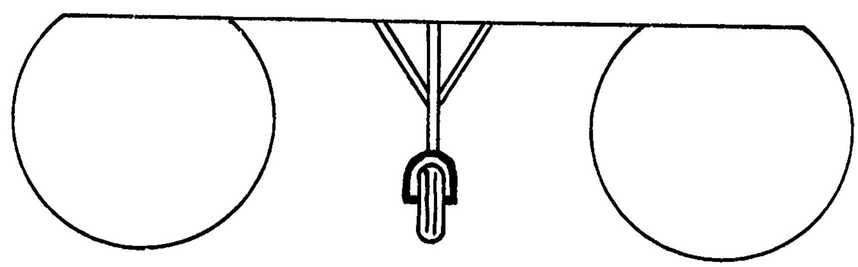
Sketch C

flow to maneuver the vehicle. For this concept, the butterfly valves in the side lobe feed hoses were adjusted to allow one side lobe to receive less flow, thus creating an asymmetric friction condition to change the vehicle heading. (See sketch D.) During this third series of tests the rudders were not used.



Sketch D

For the last series of tests, a center wheel steering concept was studied. It made use of a lightly loaded, nonsteerable, free-rolling wheel mounted in the air-bag cavity near the fore and aft center of gravity of the vehicle. (See sketch E.) The 10-in. (0.3-m) diameter wheel was attached to the strut and air cylinder assembly shown in figure 5 and was loaded vertically to approximately 200 lb (0.9 kN), 4 percent of vehicle weight, by pressurizing the air cylinder. The rudders were used in conjunction with the center wheel concept to produce the yawing moments necessary for steering.



Sketch E

TESTING TECHNIQUES

Braking

The testing technique used during the braking studies involved accelerating the vehicle down the test runway until the desired speed was reached, applying the brakes, and measuring the distance required to stop. Measurement of the elapsed stopping distance began at brake application when the forward thrust was eliminated and the trigger on the speed/distance sensing unit was activated. If the test involved braking over grass, brake application would begin after the airboat had crossed the threshhold of the runway and was running over the grass.

For each braking concept, brake application speeds ranged from approximately 15 ft/sec (5 m/sec) to 45 ft/sec (14 m/sec). In general, four tests at each speed were conducted so that representative stopping distances could be obtained.

Steering

To evaluate the performance of the steering concepts, the vehicle was maneuvered along an S-shaped path painted symmetrically about the centerline of the test runway shown in figure 6. Each straight leg of the test path was 100 ft (30.5 m) long and 50 ft (15.2 m) out from the centerline, joined by 100-ft (30.5-m) radius arcs. This maneuver was chosen because several heading and direction changes were required, and behavior differences between concepts would be apparent.

Steering tests were conducted at approximately 8, 15, and 22 ft/sec (2, 5, and 7 m/sec). For each concept, several tests were run at similar speeds with the most representative run presented in this paper. Before each test, the operator aligned the vehicle with the first leg of the maneuver while on the conventional gear. This process allowed the trailing wheel to track with no yaw relative to the vehicle. At this point the inertial reference direction was set and the instruments were calibrated. During each test, the operator accelerated to the desired speed before reaching the test path. After reaching the test path, the operator tried to maintain his speed and keep the center of the vehicle over the painted line.

DATA PRESENTATION

Braking

Parameters measured during each braking test were brake application speed and stopping distance. Equating the kinetic energy of the vehicle at the start of brake application to the work required to bring it to a stop gave the following equation:

$$1/2mV^2 = Fl \tag{1}$$

where

F = Average external force on vehicle

m = Mass of vehicle

l = Stopping distance

V = Brake application speed

The average external force on the vehicle consisted of the sum of the aerodynamic drag and the drag created between the air bag and the ground. Normalizing the average external force on the vehicle with the vehicle weight yields a coefficient that gives a measure of the stopping performance provided by each braking concept. From equation (1), the average drag coefficient for the vehicle is given by:

$$\mu_d = \frac{V^2}{2gl} \tag{2}$$

where

g = Acceleration due to gravity

Steering

To evaluate the behavior of the steering concepts, records of the actual ground path taken by the airboat were compared with the attempted steering maneuver. In figure 7, α denotes the direction of motion of the airboat relative to an absolute reference, β denotes the heading of the longitudinal axis of the vehicle, and γ denotes the angle between the longitudinal axis of the vehicle and the trailing wheel (yaw angle). Neither β nor γ gives an indication of the true direction of motion of the vehicle, but the relationship

$$\alpha = \beta + \gamma \tag{3}$$

holds true for all conditions.

Heading, yaw angle, and speed data recorded during each steering concept test were played back through an analog-to-digital convertor and fed into a desktop computer. The instantaneous heading and yaw angle were combined, multiplied by the instantaneous velocity to give a velocity vector, and numerically integrated by using small time steps, which gave a plot mapping the motion of the trailing-wheel pivot and thus the track of the vehicle. For each run, a synchronization signal was stored on tape when the trailing wheel crossed the beginning of the test path. This signal allowed a representation of the test path to be plotted over the actual vehicle track for comparison.

For each steering-concept test, the perpendicular distance between the test path and the actual track was calculated at approximately 1-ft (0.3-m) intervals. These data were used to compute average and maximum deviations.

RESULTS AND DISCUSSION

Braking

Brake application speed and stopping distance for each of the braking tests are presented in table 1. Also included in table 1 are the average drag coefficients μ_d for each braking test calculated from equation (2). The average drag coefficient appears to increase with speed, and this trend is attributed to the aerodynamic drag on the vehicle which is a function of V^2. Each braking concept was characterized by a single-value average drag coefficient $\bar{\mu}_d$. This single value is defined as the inverse of the slope of the least-squares linear curve which fits the relationship between stopping distance and the square of the brake application speed, divided by 2g.

The tests employing conventional wheels and brakes (ACLS not in use) developed an average drag coefficient of 0.22 on the concrete surface. This coefficient is consistent with routine aircraft landing decelerations and provides a basis for comparison with other braking concepts. The operator was instructed to maintain a comfortable (moderate) deceleration and to avoid locked-wheel skids; thus, this drag coefficient does not represent a maximum braking effort. Tests employing conventional wheels and brakes were not conducted on grass because of its soft surface.

To define the magnitude of the combined effects of aerodynamic drag on the vehicle and the drag created at the interface between the air bag and the ground, tare tests were conducted on concrete and grass surfaces using the ACLS but no braking effort. On concrete, the tare $\bar{\mu}_d$ was 0.05, and on grass the tare $\bar{\mu}_d$ was slightly higher at 0.09. This behavior would be expected because the blades of grass which were in contact with the air bag created an additional drag force. Also, operating on grass partially vented the cavity, which increased friction. The values of $\bar{\mu}_d$ in table 1 for each ACLS braking concept include the appropriate tare value.

Tests were also conducted to evaluate the friction coefficient between the airbag material and concrete or grass surfaces. To do this, weights up to 80 lb (0.36 kN) were placed on a 0.75-ft by 0.75-ft (0.23-m by 0.23-m) square of the airbag material and pulled along the ground. A spring scale was used to measure the kinetic pull force. On concrete, the friction coefficient was 0.42, and on grass this coefficient was 0.54. The higher value on grass may be largely attributable to the irregular surface. Neglecting air drag on the vehicle, these values represent the maximum available μ_d without air lubrication for any braking concept.

The reduced lobe flow braking concept produced a $\bar{\mu}_d$ of 0.10 on concrete. On grass, a $\bar{\mu}_d$ of 0.14 was calculated. The cavity venting braking concept produced a $\bar{\mu}_d$ of 0.21 on concrete and a $\bar{\mu}_d$ of 0.36 on the grass surface. These two concepts are among the first to be attempted at the full-scale level. A concept similar to cavity venting, referred to as suction braking, has been demonstrated at model scale. Instead of simply venting cavity pressure, a negative cavity pressure was created for braking and decelerations as high as 2g were reported (ref. 3). (1g = 32 ft/sec^2 (9.81 m/sec^2).)

The reduced lobe flow braking concept performed only about half as well as the conventional wheel braking and only took advantage of about 25 percent of the maximum available friction coefficient. The cavity venting braking concept demonstrated the capability to perform nearly as well as the conventional wheel braking and took advantage of about 50 to 70 percent of the maximum available friction coefficient.

Eighteen tests using the reduced lobe flow braking concept were conducted on concrete and some air-bag wear and occasional tears in the material (which were repaired) were observed. Eleven tests using the cavity venting braking concept were conducted on concrete. Very little air-bag wear was observed, and no tears developed. Neither braking concept produced any observable wear on the air bag during tests on the grass surface.

Steering

Data from the steering tests are presented in figure 8. The solid S-shaped curve in each plot represents the test path, and the sequence of triangular symbols denotes the actual ground track of the vehicle. The orientation of each triangular symbol indicates the instantaneous heading of the ACLS vehicle during the steering maneuver. These triangular symbols were plotted at 2-second intervals, so the spacing between each symbol is directly proportional to ground speed.

To define a baseline steering performance for the vehicle, a test was conducted using the conventional gear with nose gear steering in conjunction with the rudders (ACLS not in use). The actual and attempted steering paths for the vehicle at an average speed of 19.0 ft/sec (5.8 m/sec) are shown in figure 8(a). The average deviation for this test was only 3.5 ft (1.1 m), and the maximum deviation was 7.6 ft (2.3 m).

The steering concept using rudders only was tested at three speeds, and these results are presented in figures 8(b) to 8(d). The data indicate that rudders-only steering led to a substantial response lag during the steering maneuver as indicated by the time between the steering inputs, which altered the vehicle heading and the onset of lateral translation of the vehicle. In figure 8(b), this lag was approximately 7 seconds from the initial steering input. The average deviation for the rudders-only concept ranged from 8.6 ft (2.6 m) to 15.8 ft (4.8 m), and the maximum deviations were between 24.3 ft (7.4 m) and 27.7 ft (8.4 m). These deviations were three to five times greater than for the conventional nose-gear steering concept.

The data from the differential lobe flow steering concept are presented in figures 8(e) to 8(g). These data indicate that, with this steering concept, it was not possible to execute the desired steering maneuver. In general, the differential lobe flow steering concept failed to produce the desired heading change or a consistent lateral translation across the runway. In fact, the ACLS vehicle appeared to be more sensitive to the runway transverse slope than to the steering inputs. Average deviations ranged from 20.4 ft (6.2 m) to 22.2 ft (6.8 m), and maximum deviations were between 42.9 ft (13.1 m) and 76.6 ft (23.3 m) for this concept.

The final tests utilized the center wheel concept combined with rudders to steer the vehicle. Figure 8(h) shows a test run at an average speed of 9.0-ft/sec (2.7 m/sec). Because of his previous experience using the different steering concepts, the operator tended to anticipate the first turn and provided an early steering input which probably reduced the overall deviation. The response lag was not large, and consequently the vehicle turned prematurely. However, in general, the vehicle stayed reasonably close to the test path, and the attitude indicators showed only small amounts of yaw. The average deviation for this run was 6.6 ft (2.0 m), and the maximum deviation was 14.8 ft (4.5 m). These values are approximately twice the value of the conventional steering deviations. A test run at 14.7 ft/sec (4.5 m/sec), shown in figure 8(i), produced average and maximum deviations of 10.2 ft (3.1 m) and 26.3 ft (8.0 m), respectively. Only small deviations occurred during the first steering input, but the operator was not able to yaw the vehicle to the right rapidly enough to stay on course, and consequently spent the rest of the test attempting to get back to the test path. The deviations for this concept are approximately three times those associated with conventional steering. Figure 8(j) shows the concept performance at 26.7 ft/sec (8.1 m/sec). The operator initiated a shallow turn early, but in general did not drift too far from the test path. The average deviation was 9.3 ft (2.8 m), and the maximum deviation was 19.5 ft (5.9 m).

CONCLUDING REMARKS

An experimental investigation was conducted at Langley Research Center to evaluate the effectiveness of several concepts for braking and steering a vehicle equipped with an air cushion landing system (ACLS). The investigation made use of a modified airboat equipped with an ACLS and with a conventional retractable tricycle landing gear. Braking concepts were evaluated by measuring the distance required to stop from an initial speed and representing them as an average deceleration. Steering concepts were evaluated by attempting to follow a path painted on a runway and recording the actual ground track taken. Average and maximum deviations from the attempted path were calculated.

The ACLS braking concepts were compared with the braking performance provided by the conventional landing gear and brakes. The reduced lobe flow concept, which used butterfly valves located in the air-bag feed hoses to control the airflow, produced approximately half of the deceleration provided by the conventional system. The cavity venting braking concept, using a door located in the cavity to vent pressure, demonstrated decelerations nearly as high as the conventional technique.

The steering concepts were compared with the steering performance of the conventional nose-gear steering combined with rudders. Differential lobe flow steering proved to be ineffective. Consistent lateral translations with this concept were not achievable. Using the rudders only for steering control resulted in considerable response lags, large yaw angles, and translational deviations three to five times greater than those using the conventional steering technique. Using the rudders in conjunction with a lightly loaded, nonsteering, free-rolling center wheel proved to be a much more accurate means of steering the vehicle. Large response lags and yaw angles were eliminated, and the steering deviations were reduced to between two and three times that of the conventional nose-gear steering.

Langley Research Center
National Aeronautics and Space Administration
Hampton, VA 23665
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TABLE I.- SUMMARY OF BRAKING CONCEPT TEST CONDITIONS AND RESULTS

Concept	Surface	Speed		Stopping distance		Average drag coefficient μ_d	Single-value average drag coefficient $\bar{\mu}_d$
		ft/sec	m/sec	ft	m		
Conventional wheel braking (ACLS not in use)	Concrete	14.6	4.5	24	7.3	0.14	
		14.6	4.5	19	5.8	.17	
		14.5	4.5	22	6.7	.15	
		14.6	4.5	22	6.7	.15	
		14.6	4.5	15	4.6	.22	
		29.3	8.9	62	18.9	.22	
		29.3	8.9	56	17.1	.24	
		29.3	8.9	57	17.4	.23	
		29.3	8.9	72	21.9	.19	
		29.3	8.9	72	21.9	19	
		44.0	13.4	159	48.5	.19	
		44.0	13.4	137	41.8	.22	
		44.0	13.4	135	41.1	.22	
		44.0	13.4	131	39.9	.23	
		44.0	13.4	118	36.0	.25	0.22
No braking (ACLS in use)	Concrete	16.0	4.9	122	37.2	0.03	
		15.1	4.6	96	29.3	.04	
		14.2	4.3	99	30.2	.03	
		14.8	4.5	93	28.3	.04	
		15.7	4.8	97	29.6	.04	
		29.9	9.0	288	87.8	.05	
		28.7	8.7	302	92.0	.04	
		29.0	8.8	317	96.6	.04	
		24.8	7.6	324	98.8	.03	
		30.0	9.1	299	91.1	.05	
		44.0	13.4	543	165.5	.06	
		42.5	13.0	538	164.0	.05	0.05
	Grass	7.2	2.2	9	2.7	0.0[illegible]	
		7.6	2.3	12	3.7	.07	
		7.8	2.4	12	3.7	.08	
		15.4	4.7	59	18.0	.06	
		16.0	4.9	48	14.6	.08	
		16.2	4.9	45	13.7	.09	
		17.4	5.3	64	19.5	.07	
		24.8	7.6	142	43.3	.07	
		28.7	8.7	115	35.1	.11	0.09

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TABLE I.- Concluded

Concept	Surface	Speed, ft/sec	Speed, m/sec	Stopping distance, ft	Stopping distance, m	Average drag coefficient μ_d	Single-value average drag coefficient $\bar{\mu}_d$
Reduced lobe flow (ACLS in use)	Concrete	14.7	4.5	45	13.7	0.07	
		14.4	4.4	46	14.0	.07	
		13.9	4.2	43	13.1	.07	
		14.1	4.3	49	14.9	.06	
		15.0	4.6	43	13.1	.08	
		14.7	4.5	45	13.7	.07	
		28.9	8.8	140	42.7	.09	
		29.3	8.9	141	43.0	.09	
		30.8	9.4	151	46.0	.10	
		29.8	9.1	153	46.6	.09	
		30.0	9.1	154	46.9	.09	
		29.3	8.9	148	45.1	.09	
		43.9	13.4	283	86.3	.11	
		44.0	13.4	312	95.1	.10	
		44.7	13.6	327	99.7	.09	
		43.0	13.1	306	93.3	.09	
		44.0	13.4	305	93.0	.10	
		44.0	13.4	307	93.6	.10	0.10
	Grass	12.5	3.8	19	5.8	0.13	
		14.5	4.4	23	7.0	.14	
		14.7	4.5	23	7.0	.15	
		15.0	4.6	34	10.4	.10	
		15.7	4.8	26	7.9	.15	
		17.6	5.4	37	11.3	.13	
		18.9	5.8	46	14.0	.12	
		22.3	6.8	59	18.0	.13	
		23.2	7.1	65	19.8	.13	
		23.6	7.2	58	17.7	.15	0.14
Cavity venting (ACLS in use)	Concrete	13.2	4.0	12	3.7	0.23	
		15.1	4.6	19	5.8	.19	
		17.2	5.2	20	6.1	.23	
		21.3	6.5	28	8.5	.25	
		27.7	8.4	59	18.0	.20	
		28.9	8.8	58	17.7	.22	
		29.0	8.8	60	18.3	.22	
		42.2	12.9	142	43.3	.19	
		43.3	13.2	132	40.2	.22	
		44.6	13.6	140	42.7	.22	
		46.7	14.2	180	54.9	.19	0.21
	Grass	15.0	4.6	15	4.6	0.23	
		15.1	4.6	11	3.4	.32	
		15.4	4.7	15	4.6	.25	
		15.5	4.7	9	2.7	.41	
		16.1	4.9	12	3.7	.33	
		22.4	6.8	19	5.8	.41	
		24.5	7.5	22	6.7	.42	0.36

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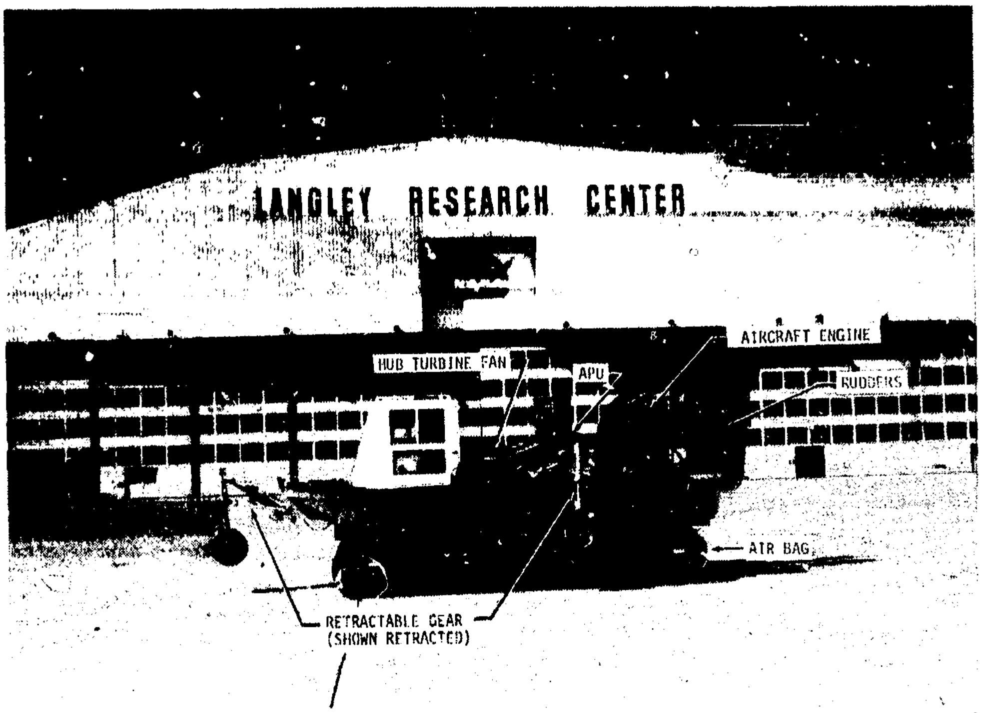
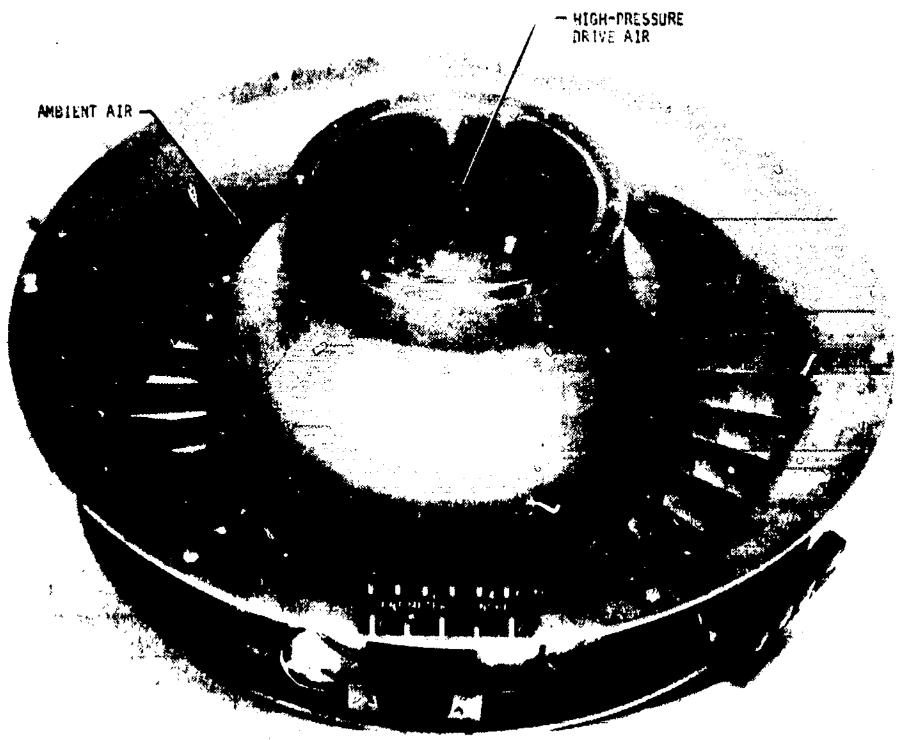


L-79-1751.1

Figure 1.- Test vehicle on air cushion landing system (ACLS).



L-82-11,959.1

Figure 2.- Hub turbine fan.

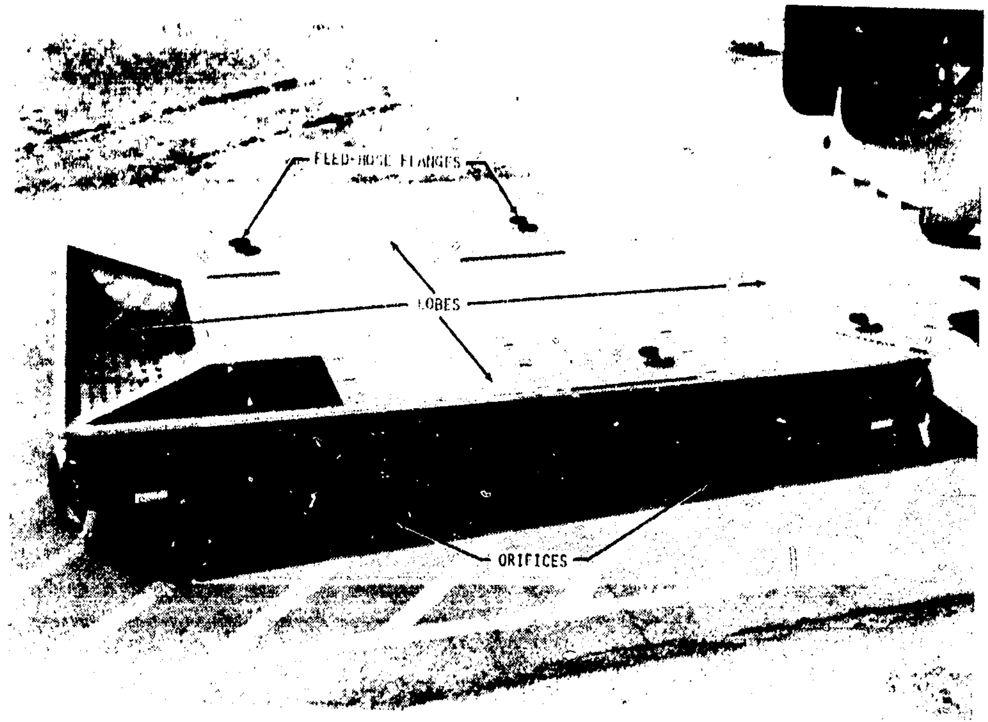


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Figure 3.- Multilobed air bag.

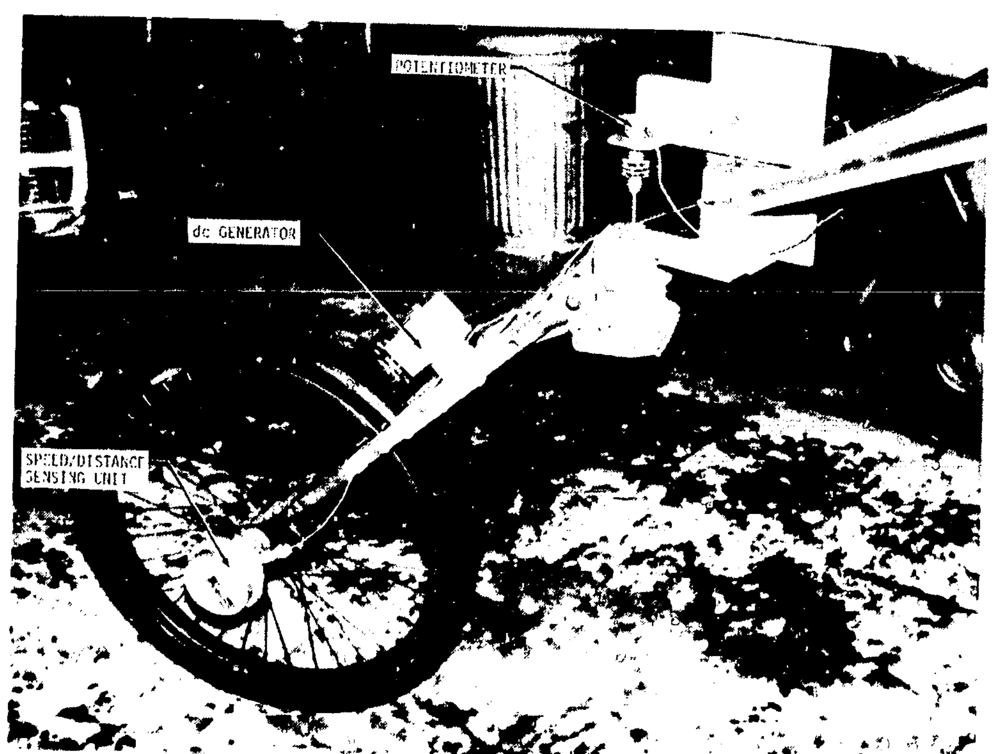

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Figure 4.- ACLS test-vehicle trailing wheel.

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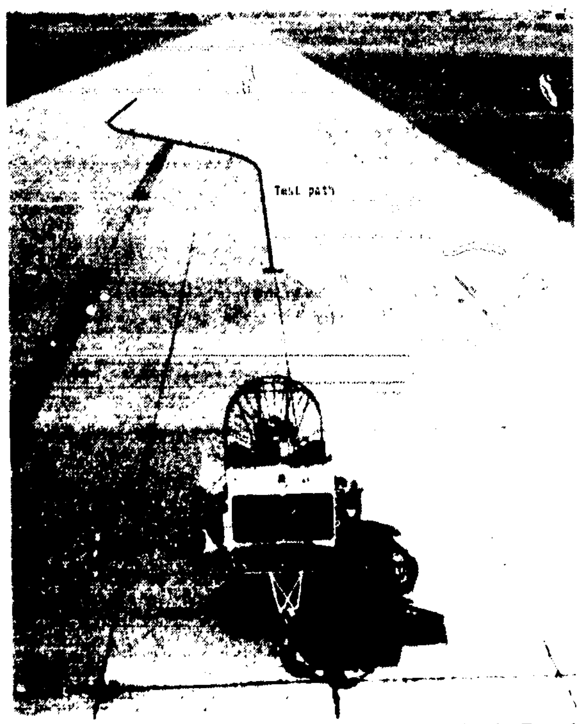
Figure 5.- Cavity vent door and center wheel.



L-82-4876.1

Figure 6.- ACLS test vehicle and test path.

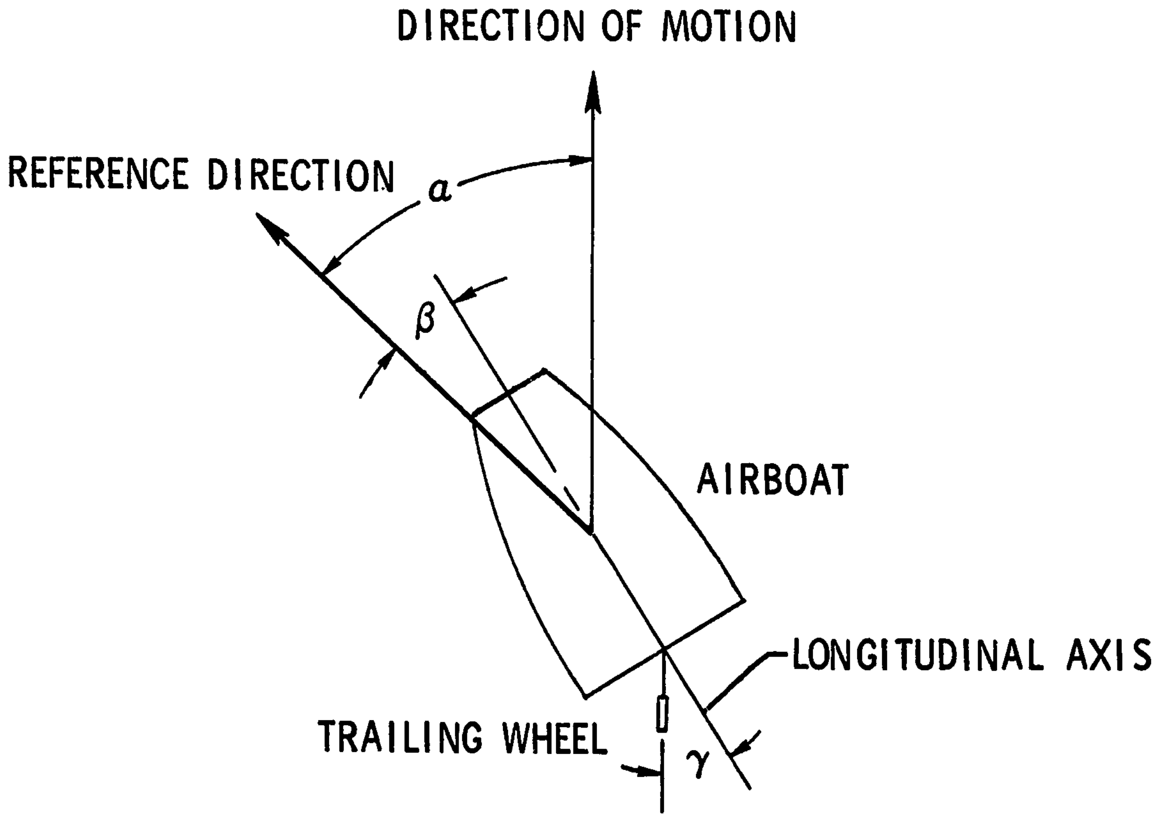
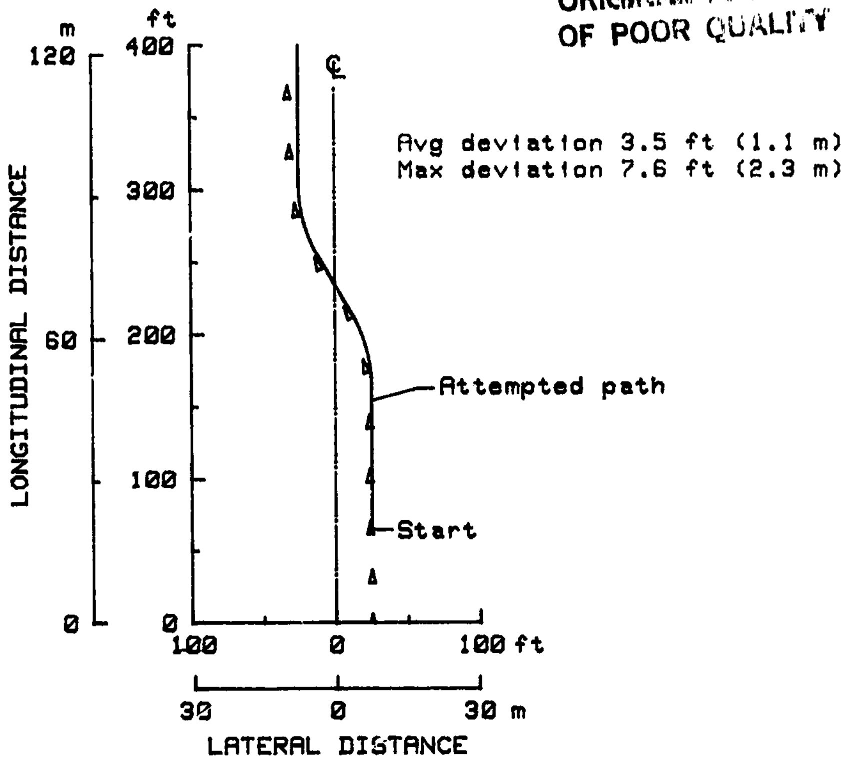
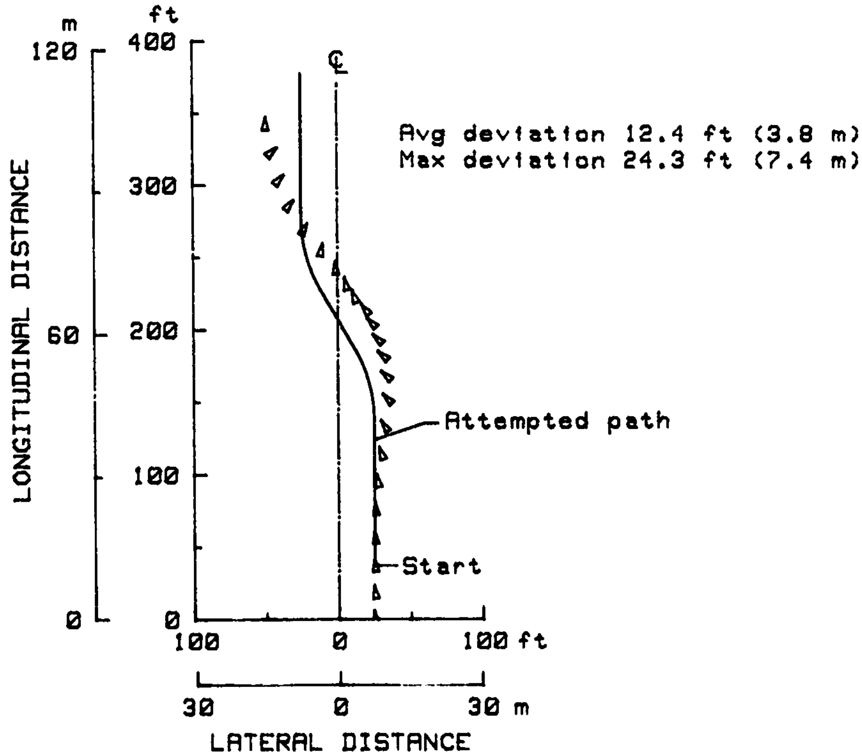


Figure 7.- Steering-angle definitions.



(a) Conventional nose-gear steering with average speed of 19.0 ft/sec (5.8 m/sec).



(b) Rudders-only concept with average speed of 8.3 ft/sec (2.5 m/sec).

Figure 8.- Steering performance plots.

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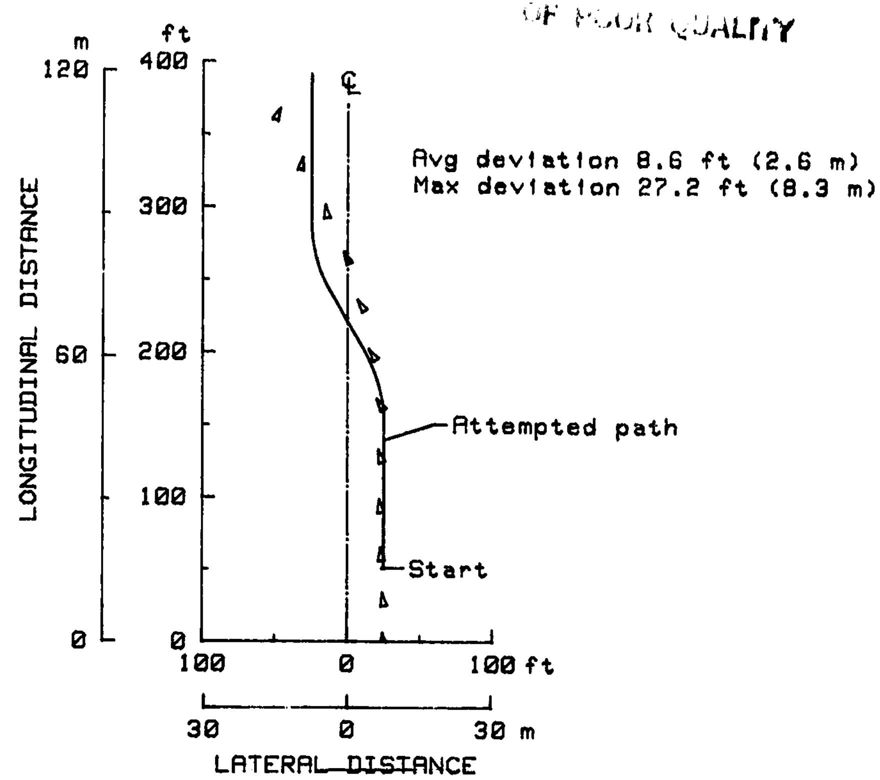
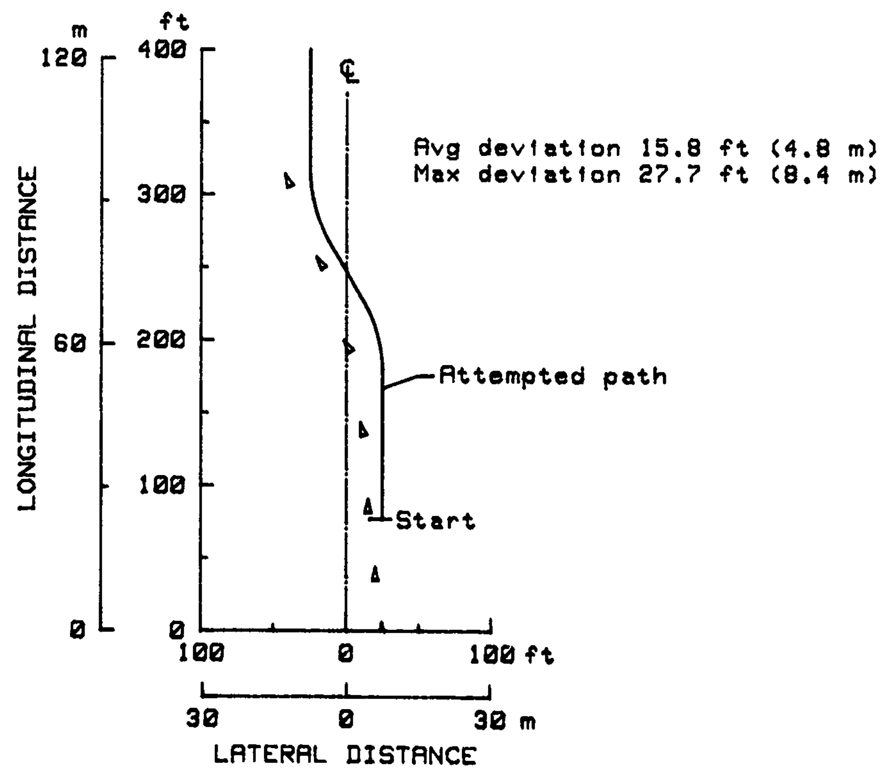
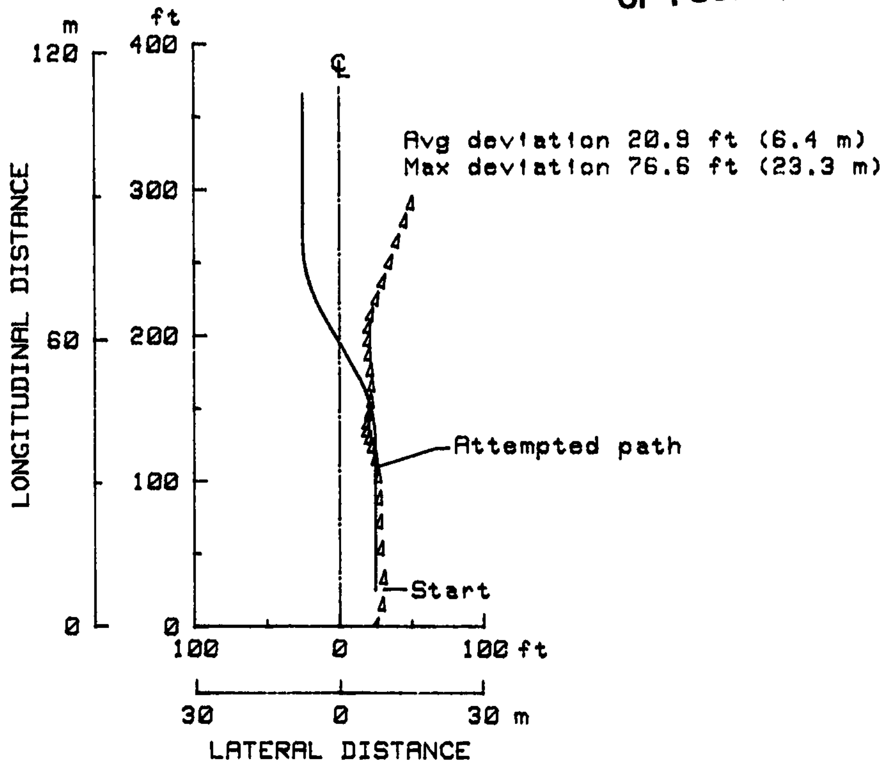


(c) Rudders-only concept with average speed of 17.1 ft/sec (5.2 m/sec).

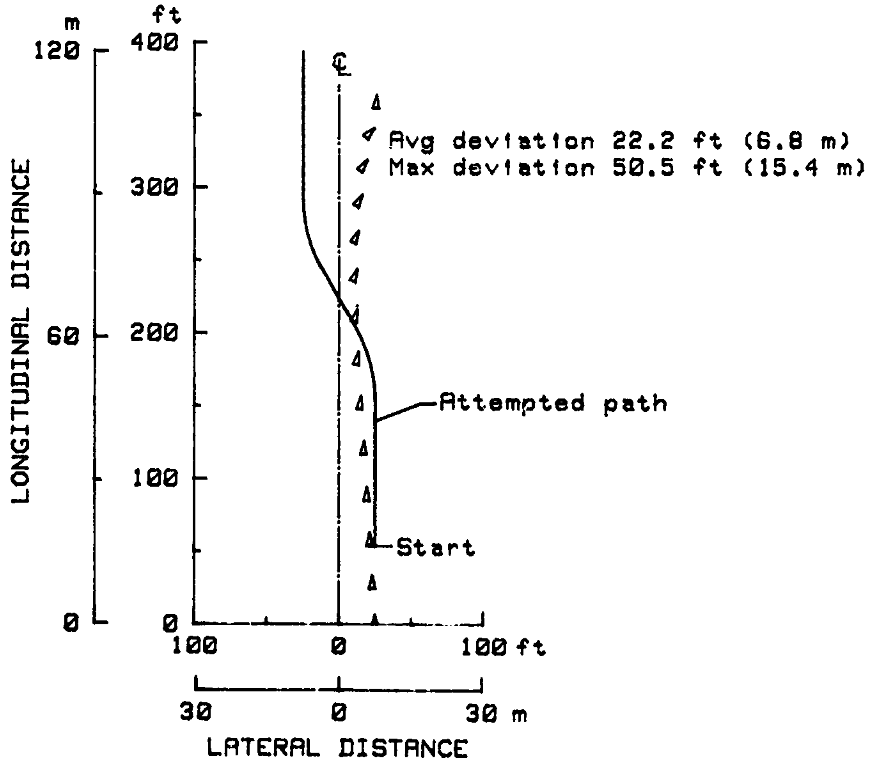


(d) Rudders-only concept with average speed of 26.8 ft/sec (8.2 m/sec).

Figure 8.- Continued.

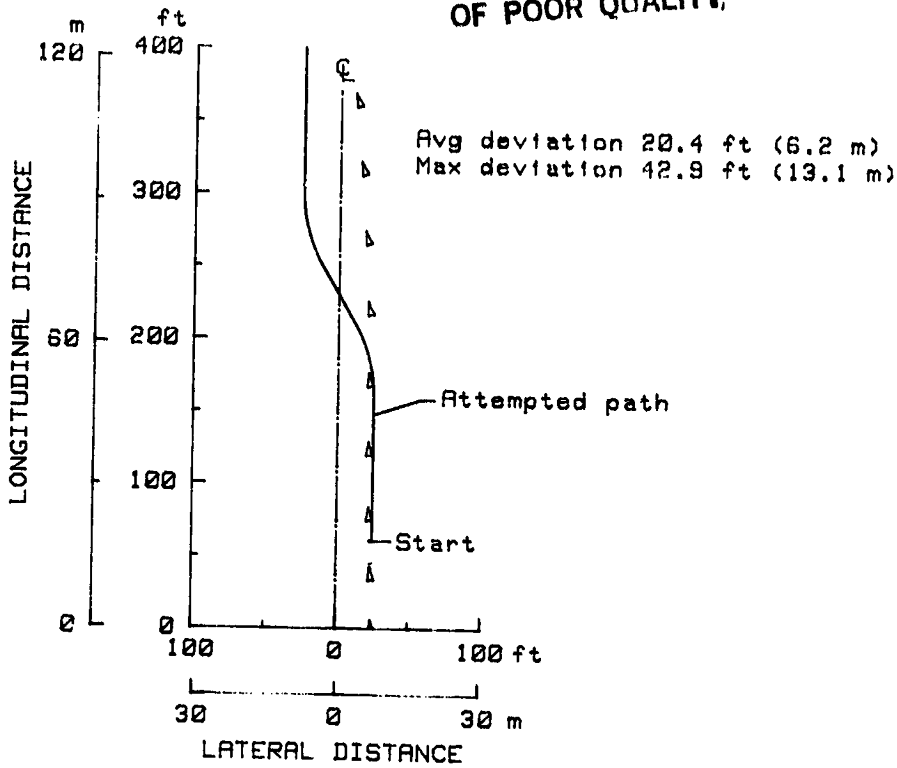


(e) Differential lobe flow concept with average speed of 6.0 ft/sec (1.8 m/sec).

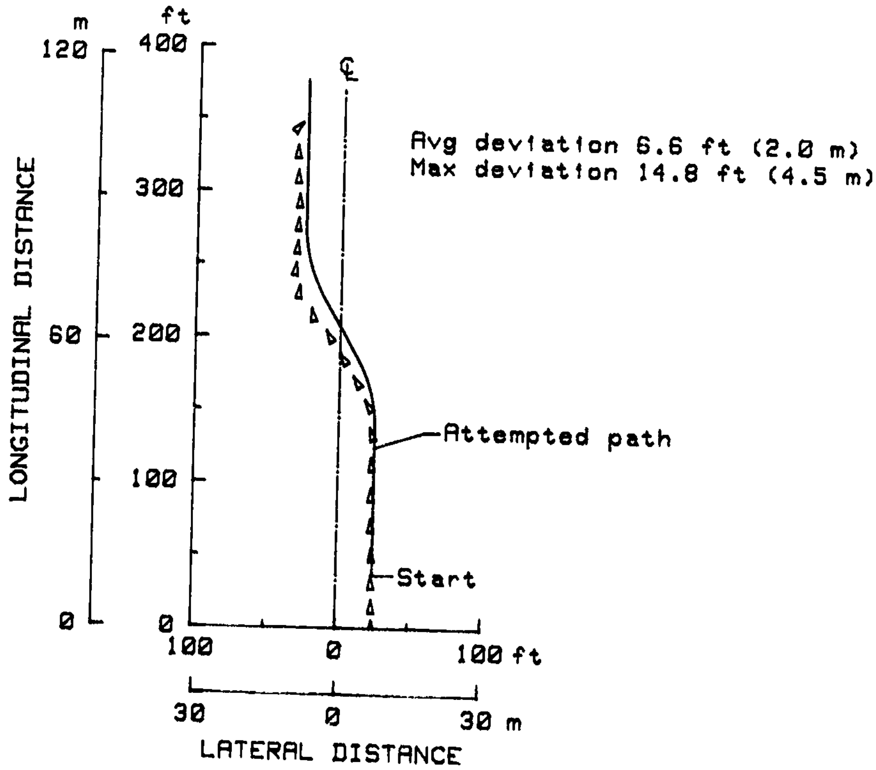


(f) Differential lobe flow concept with average speed of 13.8 ft/sec (4.2 m/sec).

Figure 8.- Continued.

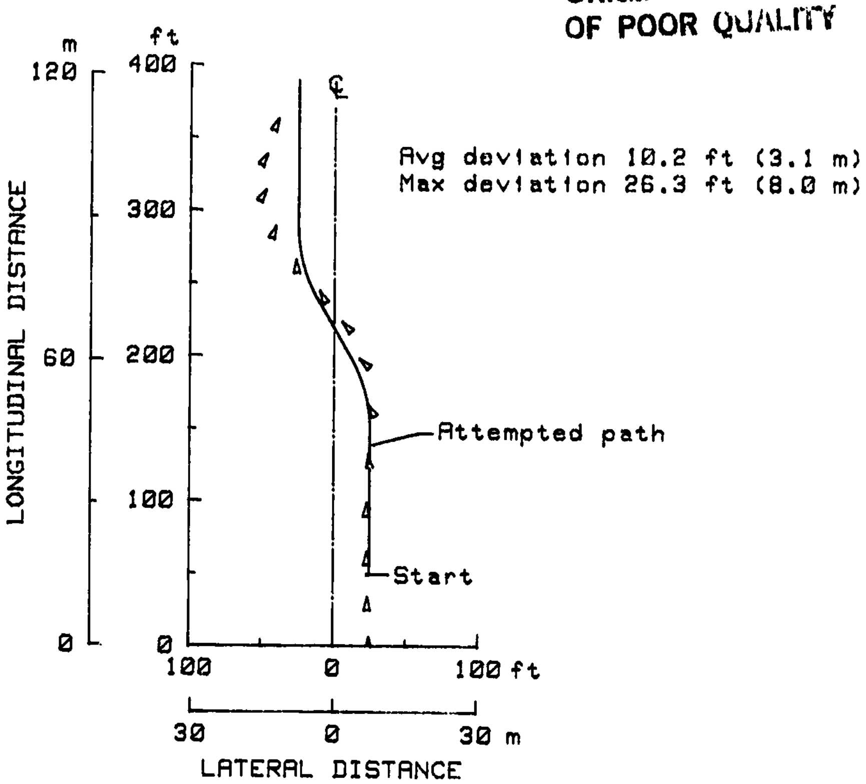


(g) Differential lobe flow concept with average speed of 22.0 ft/sec (6.7 m/sec).

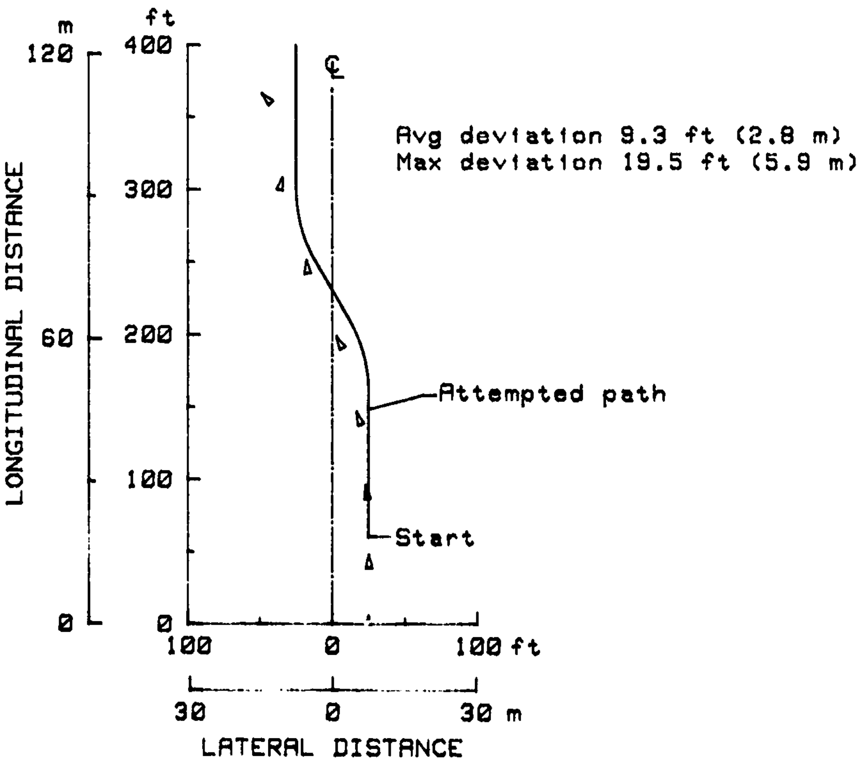


(h) Center wheel concept with average speed of 9.0 ft/sec (2.7 m/sec).

Figure 8.- Continued.



(i) Center wheel concept with average speed of 14.7 ft/sec (4.5 m/sec).



(j) Center wheel concept with average speed of 26.7 ft/sec (8.1 m/sec).

Figure 8.- Concluded.